DOCUMENT RESUME

ED 431 597 SE 062 522

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TITLE	Students' Conceptions of the "Reality Status" of Electrons.
PUB DATE	1998-00-00
NOTE	16p.; Paper presented at the Annual Meeting of the Singapore Educational Research Association (1998).
PUB TYPE	Reports - Research (143) -- Speeches/Meeting Papers (150)
EDRS PRICE	MF01/PC01 Plus Postage.
DESCRIPTORS	*Atomic Structure; Atomic Theory; Chemistry; Concept Formation; Epistemology; Foreign Countries; Matter; *Misconceptions; Physics; Science Instruction; *Scientific Concepts; Scientific Principles; Secondary Education
IDENTIFIERS	*Electrons; Ontology

ABSTRACT

Science has many explanatory concepts that have been proposed to account for the observable features of things. Such explanatory concepts often have associated with them hidden or unseen "theoretical entities." The electron is a key concept in understanding phenomena described by science. The question arises, however, as to how students make sense of such an unobservable theoretical entity. In incorporating such a concept into their overall cognitive structure, students have to address a number of questions. The implications of quantum theory for the common sense notion of an object illustrate the difficulties in using analogies taken from ordinary experience to "explain" the subatomic world. Following a review of previous research, this paper presents a study that investigated students' understanding of the "reality" of an electron as a quantum entity. Over the last 20 years there has been considerable research interest in students' perceptions of phenomena in such areas as energy, motion, the particulate nature of matter, electricity, and light; however, 90 years after the genesis of quantum physics, significant research on students' understanding of such revolutionary phenomena is only beginning to emerge. Results indicate that at the level of both ontology and epistemology students' responses appear to be predominantly Realist. The complimentary self-consistency of the findings from each of the studies also indicates that the various students' conceptions of the ontology and epistemology of entities can be characterized by particular statements. Contains 30 references. (Author/WRM)

Paper presented at the *Singapore Educational Research Association Conference 1998*
Enhancing Learning: challenge of integrating Thinking and Information Technology into the Curriculum

Students' conceptions of the 'reality status' of electrons

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Abstract

Science has many explanatory concepts that have been proposed to account for the observable features of things. Such explanatory concepts have often associated with them hidden or unseen 'theoretical entities' (e.g. atoms, electrons). The electron is a key concept in understanding phenomena described by science. The question arises however as to how students 'make sense' of such an unobservable theoretical entity.

In incorporating such a concept into their overall cognitive structure students have to address a number of questions. What are electrons 'really' like? Are electrons the same sort of object as chairs? The implications of quantum theory for the commonsense notion of an object illustrate the difficulties in using analogies taken from ordinary experience (i.e. essentially classical models) to 'explain' the subatomic world. Following a review of previous research the findings of a study investigating students' understanding of the 'reality' of a quantum entity, the electron, is presented. Over the last twenty years there has been considerable research interest in the student's perceptions of phenomena in such areas as energy, motion, the particulate nature of matter, electricity, and light. However, ninety years after the genesis of quantum physics significant research on *students' understanding* of such revolutionary phenomena is only beginning to emerge.

1 Introduction

This project is part of a larger study to construct students' conceptions of quantum phenomena, models, and the ontological and epistemological status of theoretical entities, and to explore students' implicit or underlying dimensions of reasoning. This paper is concerned with describing the 'reality' or more generally the philosophical status that students' accord theoretical entities such as electrons.

2 Theoretical entities

Theoretical concepts in science (e.g. photons and electrons) are extremely powerful tools for investigating 'reality'. The basic question concerning theoretical concepts is expressed by Wallace (1979: 52):

> ...is whether they represent something that exists outside the mind, and so can be regarded as real, or merely represent a 'being of reason' (an *ens rationis*) and so have only a fictional existence, i.e. in the mind alone and not extramentally.

The history of science has many explanatory concepts that have been proposed to account for the observable features of things, such as white, light and cool. Such explanatory concepts have often associated with them hidden or unseen entities. Phlogiston has now become viewed as a fictive entity, while molecules are mentioned in textbooks and regarded by most scientists as real as the objects of everyday experience. The electron is an extraordinarily useful concept in the explanation of electromagnetic phenomena. Wallace (1979: 59) points out that the electron is regarded by most scientists as having an extra-mental existence.

3 The labels of philosophy of science

Language can be used in a number of ways to express an individual's 'sense of reality'. The author Virginia Woolf (1957: 114), for instance, expressed it poetically:

> What is meant by 'reality'? It would seem to be something very erratic, very undependable - now to be found in a dusty road, now in a scrap of newspaper in the street, now in a daffodil in the sun.

Rather less evocatively the systematic language of the philosophy of science will be used to express the range of thinking about the 'reality' of the world, and how such knowledge is arrived at. Epistemology is about how you know what you know. Ontology is about the nature, or status, of things in the world - the what. Knowledge has both an ontological status and an epistemological justification. It is assumed that what students can know about the natural world depends upon how they know these things.

Realism is the viewpoint that proposes a direct relationship between the theoretical structures of science and the world (van Fraassen, 1980). Grover Maxwell (1962: vii) in a paper on *The Ontological Status of Theoretical Entities* advocates a position of extreme Scientific Realism:

> The thesis of this paper, bluntly put, is that electrons, photons, and even electromagnetic fields are just as real, and exist in the same full-blooded sense, as chairs, tables, or sense impressions.

The ontological opposite of Realism is Idealism. Idealism is the theory, associated especially with George Berkeley, according to which material objects have no reality beyond the ideas (sense impressions) that occur in perception. Scepticism involves the denial of the possibility of knowledge, in some realm or other. Thus, other minds Scepticism is the view that it is impossible to know the mental states of others; external world Scepticism is the view that one cannot have knowledge of reality external to one's own mind; and so on. The main ontological positions can be summarised as:

Realism	Physical objects exist independently of being observed.
Idealism	Reality is assigned only to mental phenomena.
Scepticism	Sure knowledge of how things really are may be sought, but cannot be found.

At the epistemological level Scepticism appears as 'Pragmatism' or 'Instrumentalism'. Instrumentalism views a theory as a tool and only as a tool for computation; it dispenses with the concept of truth and is uninterested in the question of reality. Pragmatists similarly are generally sceptical about the possibility of telling a 'literally true story of what the world is like' (Cherryholmes, 1992). The philosophical viewpoint of Positivism, associated with Auguste Comte, asserts the existence of a world of positive facts and phenomena with rules governing them. Furthermore that this world can be objectively ascertained through sensory perceptions, and constitutes the only source of knowledge. The extreme form of Positivism, Logical Positivism, argues that statements or propositions have meaning only if they are verifiable through empirical means (and perhaps that the meaning lies in the manner by which they would be verified). Positivism argues that Realism is a metaphysical doctrine that finds neither support nor refutation in scientific theories or investigations.

What it is thought that physics can tell an individual about the nature of the world depends on the kind of interpretation that the individual thinks can legitimately be given to the mathematical formalism of a physical theory. There is no general agreement on the interpretation of the formalism of quantum mechanics. A positivist would interpret the question 'Do electrons exist?' by replacing it with the question 'Does the theory of electrons make correct predictions?' An instrumentalist or pragmatic viewpoint would interpret talk about electrons as simply a convenient fiction for co-ordinating the results of observations. A realist interpretation would be that electrons really exist independently of theories. Since both instrumentalist and realist interpretations agree that the theory is successful a positivist would argue that is all that can be said (Mashhadi, 1997).

4 Previous research

There has been considerable research into students' conceptions of the nature of science (see Lederman, 1992 for an extensive review), but comparatively little research into the specific area of the philosophical status of entities. Using clinical interviews a number of researchers have probed adolescent and adult views of the nature of reality (Broughton, 1978; Chandler and Boyes, 1982; Kitchener and King, 1981; Kuhn *et al.*, 1988; Perry, 1970). Carey *et al.* (1989: 515) summarises these findings:

> These researchers agree that young adolescents make no differentiation between beliefs and the world, between accounts of the world and the world itself, between knowledge and reality. Differences of opinion are either not recognized, or are assumed to reflect differential access to information; the only mechanism that could yield incorrect beliefs is ignorance. In late adolescence, people become aware of genuine differences in interpretation of the same facts, genuine differences in beliefs.

Jean Piaget's researches on the genesis of the concepts of object, of space, of number, and the psychogenesis of atomism and the conservation laws provide a perspective on why certain seemingly *a priori* categories of thought apply to the macroscopic level of experience (Capek, 1971). The concept of the atom as an invisible permanent object can be apprehended only after the idea of a permanent object in general is formed. Piaget (1957: 46) in an article on *The Child and Modern Physics* remarked:

> Contemporary physicists have abandoned some old intuitions about the nature of the physical world. They have, for instance, renounced the concept of the permanence of objects in the sub-microscopic realm: a particle does not exist unless it can be localized; if it cannot be located at a particular position, it loses its title as an object and must be described in other terms. Now by an

> extremely curious coincidence it is found that a very young baby acts with regard to objects rather like a physicist. The baby believes in an object as long as he can localize it, and ceases to believe in it when he can no longer do so. The great difference between the baby and the physicist, of course, is that the baby's faculty of localization is less powerful.

Not a single feature of the classical concept of particle survived the conceptual revolution brought about by quantum physics, including the failure of intuitive corpuscular models on the microscopic scale. As Capek (1971: 452) expresses it:

> The 'particles' of modern physics are neither immutable, nor permanent, that is, neither indestructible nor uncreatable; their 'motions' cannot be traced along continuous trajectories nor can be even localized precisely. In truth, the very usage of the term 'particle' or 'corpuscle' is nothing but a mere inertia of the traditional language.

The structure of the human mind is far more flexible than is often assumed to be the case. Kant in analysing the cognitive functions of man had analysed not the *a priori* structure of mind but the modifications that are imposed upon it by our continuous interaction with the solid bodies of our macroscopic experience, what Reichenbach referred to as 'the realm of the middle dimensions' located between quanta and galaxies (Capek, 1971: 453). This cognitive structure was systematised in the Euclid-Newtonian conceptual framework. Piaget (1950: 212) points out that in speaking of the universe as a whole we are illegitimately transferring our category of object, derived from adaptation to the experienced world of macroscopic solid bodies, beyond its realm of applicability. According to Kant's theory of knowledge of the cognitive organisation of experience when objects of the real world (the 'things-in-themselves') come within the range of the sense organs of the individual they are unstructured sensations which the 'forms of intuition' (space and time) allow to be intuited as perceptions. Understanding requires judgements on the objective nature and relatedness of perceptions. Such judgements are made by a set of innate 'forms of thought' (e.g. unity, substantiality, causality and contingency) (Losee, 1980; Swift, 1986).

Piaget (1973) argued that very young children come through action and movement to develop ideas of objects and come to regard themselves as objects among other objects. Mariani and Ogborn (1990) point out that for Piaget action and movement are the 'primitives' for the first conceptualisation in childhood of fundamental categories of thought about reality. With regard to commonsense reasoning Mariani and Ogborn (1990) administered a questionnaire that asked students to indicate whether each of 36 different entities (including microscopic entities such as electrons) could belong to each of six categories. The sample consisted of 84 students in secondary schools in Italy, half were 14-15 years old and the other half were 16-17 years old. The analysis indicated that certain entities (e.g. time, electron, movement, atoms, space) were regarded as being conserved in the sense of being beyond the reach of action, and reflects its essential nature or being as a substantialisable entity:

> Examples of being beyond the reach of action include:
>
> *electron* - cannot be stopped, there are no obstacles to its movement, elementary indestructible particle...
>
> *atom* - nothing is created or destroyed, they cannot stop (*what can be done*: only transforms, changes in form)...
>
> Examples of reasons about essential nature of substantialization include:
>
> *electron* - like a planet, does not exist at rest...
>
> *atom* - has internal energy, all particles last...
>
> Reasons that see these conserved entities as causes include:
>
> *electron* - neutralizes with the proton of the atom, creates magnetic and electric fields without help, creates centripetal and centrifugal forces with the nucleus, is the basis of everything...
>
> *atoms* - matter is formed by them ...
>
> Mariani and Ogborn (1990: 60)

Mariani and Ogborn (1991) then went on to investigate the way students imagined some entities (e.g. matter, energy, time, space, movement, heat, light, sound, force) by asking a large set of very simple questions (e.g. can you see it?) about the nature of each derived from the Piagetian viewpoint that reasoning is constructed through imagined action. Using Multidimensional Scaling to uncover any underlying structure to students' responses to the questions Mariani and Ogborn (1991) argue for a simple structure of four dualistic dimensions along which the entities were distributed: dynamic *vs* static, place-like *vs* localised, cause *vs* effect, and discrete *vs* continuous. The work of Mariani and Ogborn indicates that students over a wide age range do have an ontological attitude towards entities.

Koulaidis (1987) carried out a detailed analysis of the distinctions between the main philosophical systems (see also Koulaidis and Ogborn, 1988 and 1989). With regard to the present study our interest lies in the distinctions he draws between these philosophical systems at the level of ontology and at the epistemological level with regard to the distinction between observational and theoretical entities. For instance, that at the epistemological level Logical Positivism regards observational entities (e.g. chairs) as real but views theoretical entities (e.g. atoms) as having no real existence. These distinctions were summarised by Koulaidis (1987) in a series of statements.The work of Koulaidis and Ogborn provides a framework for labelling the ontological and epistemological status of entities with respect to the principal philosophical schools of thought.

5 Methodology

The general research strategy was to use three exploratory studies (S1, S2 and S3) to build on and complement the results of previous research. The first exploratory study (S1) explored students' ideas of atoms and electrons and consisted of a semi-structured questionnaire completed by A-level Physics students (N = 57) in three secondary schools. The questionnaire utilised open and closed questions, drawings of particular situations, and attitude scales. In order to investigate further students' perceptions of the nature of 'reality' a second study (S2) was carried out with 117 A-level students in four secondary schools. Study (S2) also used some of the statements generated, from the study (S1) and the research literature, to develop the data analytical techniques and tentatively explore if there was any underlying grouping between the statements. The questionnaire, for the study (S2), consisted of 52 statements to which students responded on a five point scale. The next study (S3) explored students' ideas of photons, the nature of models and analogies, multiple models of light and the atom. The research instrument consisted of a semi-structured questionnaire completed by A-level Physics students (N = 83) in three secondary schools in October 1994. The questionnaire utilised open and closed questions, drawings of particular situations, and attitude scales. The questions in studies S1, and S3 cover a variety of topics and situations, and consist of open and closed questions. Physics textbooks, examination questions, the research literature, and the researcher's own teaching experience were used to initially construct the questions. Discussions with expert evaluators were then used to refine them.

Edwards and Mercer (1987: 4) suggest that however 'scientific' analyses based on codings seem to be, they are always dependent on prior interpretations in selecting the coding scheme to be used and in categorising sentences or utterances (see also Derrida, 1973; Ricoeur, 1981). Bearing the previous considerations in mind some numerical analysis of the data through codings was undertaken to supplement and support the qualitative interpretation. Two important preliminaries to the qualitative analysis were: gaining an intimate knowledge of the data as a whole, and building up an 'interpretive web' through reading relevant theory and previous research. An interpretative methodology was adopted for the construction of meaning from the responses to the open questions in the questionnaire. Following an initial read-through of the collated responses to a particular question the types of responses were noted. This generated an initial list of possible categories of responses. The procedure was then repeated more finely to generate categories to cover all of the students' responses. An EXCEL spreadsheet was set up and using the statistical program SPSS (Statistical Package for the Social Sciences), on the Macintosh computer, frequency distributions of responses for each question were obtained. The final stage was the production of a descriptive summary of the overall findings, which included quotations from the questionnaires to illustrate particular conceptions. It should be borne in mind that the summary statements characterising students' conceptions represent a much reduced description of students' responses to questions. As Watts (1982: 14) commented on the 'pithy summary statements' he used to characterise children's conceptions of energy:

> The framework here came from no one pupil. They have been placed together from the implicit and explicit conceptions used by the children during the course of the interviews...The frameworks are not intended as discrete and mutually exclusive categories of interview responses. This is an important point. The expressions youngsters use can be classified in a number of ways.

The principal problem of interpretive studies attempting to elicit students' conceptions is the hermeneutic circle - the researcher's knowledge of students' conceptions is dependent on the researcher's constructions, which are based on the researcher's conceptions (Johansson, Marton and Svensson, 1985). The validity of the findings is addressed by seeing if the conceptions identified are consistent with previous studies, and by ensuring the transparency of the process of interpretation. As useful preliminaries to the qualitative analysis an intimate knowledge of the data as a whole is obtained, and an 'interpretive web' built up through reading relevant theory and previous research. The interpretative technique has been used elsewhere and is accepted by the community of science educators as a method for constructing meaning. The validity of the generated conceptions is underscored by the complementary use of qualitative and quantitative techniques (Reichardt and Cook, 1979). As an additional form of 'triangulation' peer discussion is used to enhance validity of interpretation. A systematic method of analysis, coupled with accessibility to the research data for peer review attempts to establish the rigour of this study.

6 Students' conceptions of the ontological status of electrons

An open question asked in the first study (S1) proposed a situation in which a student wonders whether J. J. Thomson had discovered or invented the electron. In other words, is reality of an objective nature, or the result of individual cognition? The ontological 'nominalist' view argues that objects of thought are merely words and that there is no independently accessible thing constituting the meaning of a word. The opposing 'realist' view holds that objects have an independent existence and are not dependent for it on the knower. The difficulties that face students in considering the electron were perceptively remarked upon by one student:

> Maybe the student was stupid and couldn't believe that something so unimaginable exists. Or maybe he was clever and believed that when there are so many contradictory things about electrons, it is hard to define one. Maybe if I knew about sub-atomic theories it would be easier to understand electrons.

A substantial majority of students (~60%) in responding to the question used the word 'discover' in the sense of 'un-cover', that is, unveiling or becoming aware of something that was there, fully formed, beforehand (i.e. a Realist viewpoint). These students felt that the electron had always existed, Thomson had perhaps named it. A typical comments argued:

> He did not invent it. He merely named the phenomena, something that is invented is something that is made by man. The student could think he invented it because J. J. Thomson was trying to simplify various things into one name and labelling all the phenomena an 'electron'.

Most of the other students (~28%) felt that the concept of the electron had been invented in order to co-ordinate the results of observations or 'explain' the phenomena:

> Because he could not see it. He saw something happen and explained this by suggesting that it was caused by what he called an electron it was not a case of he found it but he made up the idea to account for something.

Electrons on this viewpoint would be a convenient fiction to explain the phenomena or to make correct predictions, i.e. the epistemological positions of Instrumentalism and Positivism. The above analysis of students' responses to an open question in the first exploratory study (S1) seems to indicate that they cover the epistemological positions of Scientific Realism, Positivism and Instrumentalism. At the level of ontology students' responses appear to be predominantly Realist.

In order to investigate further students' perceptions of the nature of 'reality' a second complementary study (S2) was carried out with a different population sample. A series of statements were constructed as a result of the analysis of the first exploratory study (S1), and the literature review. The statements were designed to reflect, and thereby enable the students to respond to, a number of philosophical positions at both the levels of ontology and epistemology. There are advantages and disadvantages in using open questions. For instance, although at the ontological level the students seem to be expressing a Realist position concerning electrons, they have not had an opportunity to disagree with the positions of Idealism and Scepticism. Having specific statements also enables students to respond to the distinction between Positivism and Instrumentalism. The questionnaire as a whole consisted of 52 statements to which students responded on a five point scale (i.e. strongly agree to strongly disagree). However only ten of the statements are of relevance to the research questions being discussed here concerning the ontology, and epistemology of entities with regard to a spread of philosophical positions.

In response to a statement which suggested that the world of nature exists independently of human thoughts just over two-thirds (69%) of the students agreed that it does (i.e. agreed with the ontological position of Realism). In response to a statement that proposed that no objects exist independently of thought only 17% of the students agreed with this proposition (i.e. agreed with the ontological position of Idealism), while most students either disagreed (31%) or had no strong opinion (50%). A statement that corresponded to the ontological position of Scepticism gave rise to equal numbers of students agreeing and disagreeing with the statement (38%). The most strongly held and clearly held position by the students at the level of ontology was, therefore, that of Realism. A more weakly and ambiguously held position was that of Scepticism, while that of Idealism was the weakest. The results obtained from study (S2) are, therefore, consistent with those of study (S1).

7 Students' conceptions of the epistemological status of electrons

In study (S2) the students were also presented with a series of statements on the epistemological status of entities. At this epistemological level a statement that reflected a position of Scientific Realism (i.e. both photons and chairs exist) was overwhelmingly agreed to by the students (86%). Similarly students agreed with statements that proposed that an electron exists even when it is not being observed (77%), and that the electron was discovered, not invented (80%). In complete contrast the position of Logical Positivism in which only things that can be observed can be considered to exist was agreed to by only 7%, and disagreed to by 90% of students. Opinions were more evenly divided on a statement, again on Logical Positivism, that suggested that it is not the task of physics to find out how nature is, with one-third of the students agreeing and one-third having no strong opinion on the matter (24% disagreed). Also when asked if the better of two theories is the one which gives the more useful results, reflecting an Instrumentalist position, just under one-third of the students (31%) agreed while just over one-third (41%) disagreed (27% had no strong opinion). At the epistemological level, therefore, the position of Scientific Realism is held most clearly and strongly by this sample of students.

In a follow-up complementary study (S3), with a different population sample, students were asked to respond to a question which contained statements about the epistemological status of electrons that related to the philosophical positions of Positivism, Instrumentalism, and Scientific Realism respectively:

> A The theory of electrons is only useful in making correct predictions.
>
> B Electrons are a convenient fiction for co-ordinating the results of observations.
>
> C Electrons really exist independently of theories.

The students were asked to state which statement they most agreed with, and give reasons for their choice.

Approximately half the students (49%) regarded electrons as really existing independently of theories (i.e. the epistemological position of Scientific Realism). Typical comments by students to justify their choice were:

> They probably do exist as they probably need to for the reactions of experiments etc. to happen, but they must have been found through people thinking up theories about reactions and proving them through electrons being there.

Just under a third of the students (27%) felt that electrons are a convenient fiction for co-ordinating the results of observations (i.e. Instrumentalism):

Although we think that they do not exist they are a very good way of understanding the way things react.

Most of the remaining students (19%) viewed the theory of electrons is only useful in making correct predictions (Positivism):

Electrons have never been seen before so they are fictitious and are used to explain observations and reactions.

The principal explanations given by the students (accounting for 59% of responses) for their choice of the philosophical status of electrons are that:

1. Electrons have been proven to exist, as their existence is consistent with theories, observations or known truths (i.e. Scientific Realism) (17% of students).

   They must exist as their properties fit in with all theories and known truths that exist.

2. Electrons have not been proven to exist, but they help to explain the properties of atoms or the way things react. It is very difficult to prove their real existence as they are very small and have not been seen (i.e. Instrumentalism) (16% of students).

   Electrons have not been proven to exist but they relate to what people think happens in an atom and helps to give the atom properties.

3. Electrons help to make correct predictions and analyse results and observations (Logical Positivism) (16% of students).

   The use of the theory of electrons is often useful in not only predicting, but also in analysing results and observations.

4. We are taught that electrons really do exist (i.e. uncritical acceptance of Realist position) (~ 10% of students).

   Because I believe teachers when they say electrons exist.

Minority explanations given were that:

5. The concept has been named, therefore whatever is there will be electrons (~ 1% of students).
6. Electrons have been seen by an electron microscope (~ 1% of students).
7. Electrons are only encountered in theories, but that does not mean that they do not exist (~ 2% of students).
8. Do not agree with the other two statements (~ 5% of students).
9. We do not know what electrons look like, so we might never know the truth (~ 5% of students).

10. Electrons are considered as particles only for convenience (~ 1% of students).
11. Things exist without people knowing about them (~ 5% of students).
(No response by one-fifth of students).

The results of the study (S3) are consistent with the findings from studies (S1) and (S2). From each of the studies a consistent picture emerges of Scientific Realism being the dominant epistemological position held by students. The Instrumentalist viewpoint is adopted by some students, while only a minority of students appear to agree with Logical Positivism.

8 Conclusion

At the level of both ontology and epistemology students' responses appear to be predominantly Realist. The complementary self consistency of the findings from each of the studies also indicates that the various students' conceptions of the ontology and epistemology of entities can be characterised by particular statements.

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Title: STUDENTS' CONCEPTIONS OF THE 'REALITY STATUS' OF ELECTRONS

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Corporate Source: PAPER PRESENTED AT THE SINGAPORE EDUCATIONAL RESEARCH ASSOCIATION CONFERENCE 1998

Publication Date: 1998

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